Variable Stars in the Newly Discovered Milky Way Dwarf Spheroidal Satellite Canes Venatici I[1]

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ABSTRACT

We have identified 23 RR Lyrae stars and 3 possible Anomalous Cepheids among 84 candidate variables in the recently discovered Canes Venatici I dwarf spheroidal galaxy. The mean period of 18 RRab type stars is $\langle P_{ab}\rangle = 0.60 \pm 0.01$ days. This period, and the location of these stars in the period-amplitude diagram, suggest that Canes Venatici I is likely an Oosterhoff-intermediate system.

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[1]Based on data collected at the 2.3m telescope at the Wyoming Infrared Observatory (WIRO) at Mt. Jelm, Wyoming, USA, and at the INAF-Telescopio Nazionale Galileo and the 4.2m William Herschel Telescope, at Roche de los Muchachos, Canary Islands, Spain.

The average apparent magnitude of the RR Lyrae stars, $\langle V \rangle = 22.17 \pm 0.02$ mag, is used to obtain a precision distance estimate of 210^{+7}_{-5} kpc, for an adopted reddening $E(B-V)$=0.03 mag. We present a B, V color-magnitude diagram of Canes Venatici I that reaches $V \sim 25$ mag, and shows that the galaxy has a mainly old stellar population with a metal abundance near [Fe/H] = −2.0 dex. The width of the red giant branch and the location of the candidate Anomalous Cepheids on the color-magnitude diagram may indicate that the galaxy hosts a complex stellar population with stars from $\sim$ 13 Gyr to as young as $\sim$ 0.6 Gyr.

1. Introduction

The Canes Venatici I (CVn I) dwarf spheroidal (dSph) galaxy (R.A.= $13^{\rm h}\ 28^{\rm m}\ 03.5^{\rm s}$, decl. = $38^\circ\ 33'\ 33.21''$, J2000.0; ℓ= 74.3°, b= 79.8°), discovered by Zucker et al. (2006), is one of the new satellite companions to the Milky Way (MW) that have been revealed from analysis of deep imaging obtained with the Sloan Digital Sky Survey (SDSS) (Belokurov et al. 2007). Zucker et al. (2006) found CVn I to have an absolute magnitude, $M_v = -7.9 \pm 0.5$ mag and a central surface brightness of $\sim$ 28 mag arc-second^{-2}, slightly fainter than the well known dSph galaxies Draco and UMi, but brighter than other recently discovered dSph galaxies. The galaxy has a half-light radius r_h= $8.5' \pm 0.5'$, with ellipticity 0.38 and overall extent along the major axis of $\sim$ 2 kpc (Zucker et al. 2006). The SDSS $i, g-i$ color-magnitude diagram (CMD) showed CVn I to be at a large distance (220 kpc), with a morphology suggesting a dominant old stellar population. However, de Jong et al. (2007), applying an automated numerical CMD analysis technique to the SDSS data, also suggested the possible presence of a younger stellar component about 2.5−4 Gyr old. The CVn I CMD exhibits a well-populated horizontal branch (HB), which extends across the region of the RR Lyrae instability strip, raising the possibility that CVn I contains a significant RR Lyrae population. RR Lyrae stars, indicative of an old stellar population, have been found in all the dSph systems identified prior to the recent SDSS discoveries, as well as in the newly discovered Boötes dwarf (Siegel 2006; Dall'Ora et al. 2006), which is the only one of the new SDSS dSph's to have been searched thus far for variable stars. Although MW globular clusters with significant numbers of RR Lyrae stars exhibit the well-established Oosterhoff dichotomy (Oosterhoff 1939), many (but not all) of the dSph galaxies have Oosterhoff-intermediate properties (see Catelan 2005). Notably, the Boötes dSph is in fact an Oosterhoff type II (OoII) system (Siegel 2006; Dall'Ora et al. 2006).

In this *Letter* we present the first results of a search for variable stars in CVn I, and use the RR Lyrae stars that were discovered to establish its Oosterhoff classification. We

also present a B, V CMD of CVn I extending to $V \sim 25$ mag. This is about 3 magnitudes fainter than the CMD of Zucker et al. (2006) and allows us to obtain insight on the stellar components of CVn I by fitting the galaxy CMD with theoretical isochrones of different metallicity and age.

2. Observations and Data Reduction

B, V, and Cousins I time-series photometry of CVn I was obtained in 2006 May and 2007 April and May at the 2.3 m Wyoming Infrared Observatory telescope (WIRO), using WIRO-Prime, the prime focus CCD camera (Pierce & Nations 2002). Additional B, V, I photometry was obtained at the 3.5 m Telescopio Nazionale Galileo (TNG) in 2006 April using the Device Optimized for the LOw RESolution (DOLORES), and at the 4.2 m William Herschel Telescope in 2007 April using the Prime Focus Imaging Camera. The WIRO observations cover a field of view measuring approximately 17.8 by 17.8 arcmin in size. The TNG and WHT observations cover areas of 9.4 by 9.4 arcmin and 16.2 by 16.2 arcmin, respectively. We obtained 43 V, 22 B and 15 I frames in total, corresponding to total exposure times of about 9^h, 4.4^h and 2.7^h, in V, B and I respectively. The images were bias subtracted and flat-field corrected using IRAF.[11]. Fringing in the I-band images was corrected using a fringe map for each image. Peter Stetson's DAOPHOT II/ALLSTAR packages (Stetson 1987, 1992) were used to obtain instrumental magnitudes for each star. These were transformed to the standard system using observations of the Landolt standard fields PG1323, PG1633, and SA104 (Landolt 1992) at WIRO, and PG0918 and PG1633 at the WHT. The observed standard stars were then used to derive the calibration equations for each telescope. Typical errors at the level of the CVn I HB ($V \sim 22.2$ mag) for the combined photometry of non-variable stars are σ_V= 0.01 mag, σ_B= 0.01 mag, and 0.015 mag, 0.03 mag, in the WHT and WIRO datasets, respectively.

3. Variable Stars

We used the V-band time series, which had more phase points than the other bands, to identify variable stars using Peter Stetson's ALLFRAME/TRIAL package (Stetson 1994). A total of 84 candidate variables were identified. The majority of these had brightnesses

[11]IRAF is distributed by the National Optical Astronomical Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

and colors consistent with positions on the HB, but not all of these stars had a sufficient number of good observations for the determination of periods. Period searches were carried out using Supersmoother (Reimann 1994). The resultant light curves were fit to template light curves (Layden 1998) in order to classify the type of variable star; these classifications were confirmed by eye. By this procedure we obtained reliable periods and light curves for 23 RR Lyrae stars: 18 fundamental-mode (RRab) variables and 5 first overtone (RRc) stars. Comparatively few RRc variables were identified compared to RRab stars, since we had greater difficulty in establishing reliable periods for RRc candidates due to aliasing problems; their number may therefore be underestimated. For these variables there are typically 36 observations in the V band, with 22 and 10 observations in the B and I bands, respectively. Three brighter variables about 1.5-2 magnitudes above the galaxy's HB were also identified. They are possibly Anomalous Cepheids (ACs), but have incomplete phase coverage. According to the position on the galaxy's CMD, the vast majority of the remaining 58 candidate variables are likely RR Lyrae stars. Example light curves for some of the identified variables are shown in Figure 1. The average periods for the RR Lyrae stars are: $\langle P_{ab} \rangle = 0.60 \pm 0.01$ days ($\sigma = 0.02$ days) and $\langle P_c \rangle = 0.38 \pm 0.01$ days ($\sigma = 0.03$ days). The average period for the RRab's suggests that CVn I is an Oosterhoff-intermediate object. The period-amplitude relation for the V-band is shown in Figure 2. The majority of the CVn I RRab stars fall in the region between the Oosterhoff type I (OoI) and Oosterhoff type II (OoII) loci, supporting the classification of CVn I as an Oosterhoff-intermediate object. CVn I would be in this sense like the majority of dSph systems previously searched for RR Lyrae stars (Catelan 2004), but unlike the recently discovered Boötes system, which belongs to the Oosterhoff II class (Siegel 2006; Dall'Ora et al. 2006).

4. Structure and Color-Magnitude Diagram

Figure 3 shows a map of the CVn I stars in the field of view of the WHT observations. A smoothing filter was applied to the data to enhance the stellar densities over the background. Although the half-light radius of CVn I (r_h= $8.5' \pm 0.5'$, Zucker et al. 2006) exceeds the WHT field of view, the bulk of the CVn I stars appears to be inside the elongated structure outlined by the black ellipse of Figure 3, whose semi-major axis measures $\sim 6.7'$. Figure 4*a* shows the $V, B-V$ CMDs of the CVn I dwarf spheroidal galaxy obtained from stars in the whole 16.2 $\times$ 16.2 arcmin^2 field covered by the WHT observations (Fig. 4*a*), and in 3 separate regions corresponding to the black ellipse region (Fig. 4*b*); the intermediate region between ellipse and circle (Fig. 4*c*); and the region outside the blue circle (Fig. 4*d*). The three regions cover areas in the ratio 1:1:1.5. Only stars with σ_V, $\sigma_B \leq 0.10$ mag, $\chi \leq 2$, and shape-defining parameter $\mid SHARP \mid \leq 0.5$ are plotted in the figure.

The galaxy CMD reaches $V \sim 25$ mag, is very rich in stars and confirms that the dominant population in CVn I is old. The galaxy has well-populated horizontal and red giant branches. The HB stretches across the RR Lyrae instability strip, which is entirely filled by the large number of candidate RR Lyrae stars, and extends significantly to the blue. The red giant branch (RGB) is a prominent feature of the CVn I CMD, and exhibits some scatter. Its width suggests the existence of a composite population in CVn I, with stars having some spread in metallicity and/or age. The galaxy CMD is very crowded below $V =$ 24 mag, but nevertheless shows hints of a young main sequence at $B - V \sim 0.2$ mag, thus providing support for de Jong et al.'s (2007) earlier suggestion. From the average luminosity of the HB ($V_{HB} \sim 22.2$ mag), the turnoff of the old stellar population is estimated to lie a few tenths below the limiting magnitude reached by our photometry. Contamination by field stars is clearly seen in Fig. 4*a*, with stars from the MW disk dominating for $B - V > 1.2$ mag, and stars from the Galactic halo contaminating the CVn I CMD at bluer colours. Since the field of view covered by our observations does not extend beyond $\sim 8.9'$, we do not have a control field devoid of galaxy's stars to discuss the field contamination properly. In order to minimize contamination by field stars and to take into account the elongated structure of CVn I, in Fig. 4*b* we have considered only stars within the black ellipse. The main features of the galaxy CMD, including the blue plume of a young stellar component, shows up much more clearly in Fig. 4*b*. This component becomes increasingly prominent moving outward (see Figs. 4*c* and 4*d*). The contamination by the MW disk is also significantly reduced in Fig. 4*b*. Synthetic CMDs of the MW field at the position of CVn I show that a large fraction of the bright stars at $V \sim 20$ mag and $B - V \sim 0.4 - 0.5$ mag in the galaxy CMD is accounted for by MW halo stars and foreground galaxies (M. Cignoni, private communication). In Fig. 4*b* we have plotted in red stars of the Galactic globular cluster M68, from Walker (1994), shifted in magnitude (by -6.58 mag) and color (by -0.04 mag) to match the CVn I horizontal and red giant branches. The RGB of M68 provides an excellent fit to CVn I, implying that the old population in the galaxy has a metallicity close to that of M68: [Fe/H] = -2.1 or -2.0 dex on the Zinn & West (1994) and Carretta & Gratton (1997) scales, respectively. Since the reddening of M68 is E(B-V)=0.07$\pm$0.01 mag (Walker 1994), the -0.04 mag color shift required to match the CVn I and M68 CMDs implies a reddening E(B-V)=0.03$\pm$0.02 mag for CVn I. This is slightly larger than the 0.014 ± 0.026 mag value derived for the galaxy from the Schlegel et al. (1998) maps.

Recent spectroscopic analysis of stars in CVn I (Ibata et al. 2006; Martin et al. 2007) distinguished two separate components in CVn I with $-2.5 <$ [Fe/H] < -2.0 dex and $-2.0 <$ [Fe/H] < -1.5 dex, respectively, on the Carretta & Gratton (1997) scale. These results were contested by Simon & Geha (2007), who found no evidence for a second metallicity component in CVn I, based on a sample of stars three times larger than that considered

by Ibata et al. (2006) and Martin et al. (2007). Using the Rutledge et al. (1997) technique (which is consistent with the Carretta & Gratton 1997 metallicity scale), Simon & Geha (2007) obtained [Fe/H] = -2.09 ± 0.02 dex, with dispersion $\sigma_{\rm [Fe/H]}$= 0.23 dex. This metal abundance is in good agreement with the metallicity we infer from the comparison with M68. Our CMD and the comparison with M68 do not provide evidence in favor of two separate components with differences in metallicity as large as claimed by Ibata et al. (2006) and Martin et al. (2007) in CVn I. In order to investigate this point further, and to possibly disentangle the age and the metallicity effects, we have fitted isochrones from the PISA database[12](Cariulo, Degl'Innocenti, & Castellani 1997) to the CMD of CVn I in Fig. 4*a*, varying the metallicity in the range from Z=0.0002 to Z=0.0004 and the age from 13 to 0.6 Gyr. Results of the best fit are shown in Figure 5, where we also show the variable stars of CVn I in different symbols.

The best-fit procedure does not favor significant metallicity spreads among the CVn I stars. The galaxy CMD is best reproduced by the superposition of 4 subsequent generations of stars with roughly the same metal abundance, Z=0.0002 ([Fe/H]=$-$2.0 dex). They include: a 13 Gyr component (red isochrone) accounting for the redder RGB, the HB and the RR Lyrae stars; a 5 Gyr population (blue isochrone) producing the bluer RGB and the fainter portion of the red clump; 1.5 Gyr stars (green isochrone) providing part of the blue plume and the brighter portion of the red clump; and, finally, a 0.6 Gyr component (black isochrone) producing the bluest part of the blue plume and the ACs. A deeper CMD is needed to fully confirm this interpretation.

5. An Improved Distance Estimate for CVn I

The intensity-weighted mean magnitude of the Canes Venatici RR Lyrae stars is $\langle {\rm V} \rangle$ = 22.17 $\pm$0.02 mag (with a dispersion of 0.07 mag among the 23 stars). We adopt an absolute magnitude of $\rm M_V = 0.46 \pm 0.03$ mag for RR Lyrae stars with metallicity [Fe/H] = -2.1 dex (Cacciari & Clementini 2003). We assume a reddening for CVn I of $\rm E(B-V) = 0.014 \pm 0.026$ mag (Schlegel et al. 1998), with consequent absorption in the V band of about 0.04 mag. We thus find a distance modulus of $\mu_0 = 21.67 \pm 0.06$ mag, which corresponds to a distance of $d = 216^{+7}_{-5}$ kpc. This agrees with the distance of 220^{+25}_{-16} kpc found in Zucker et al. (2006), which is also based on the Schlegel et al. (1998) reddening. If we adopt instead the value of $E(B-V)$=0.03 $\pm$ 0.02 mag inferred from the comparison with M68, we obtain a distance modulus of $\mu_0 = 21.62 \pm 0.06$ mag, and in turn a distance of $d = 210^{+7}_{-5}$ kpc.

[12]http://astro.df.unipi.it/SAA/PEL/Z0.html

6. Conclusions

We have identified and obtained periods and light curves for 18 RRab stars and 5 RRc stars in the Canes Venatici I dSph galaxy. We also identified three potential Anomalous Cepheids and 58 additional candidate variable stars that according to their position on the galaxy CMD are very likely RR Lyrae stars. The average period of the CVn I RRab stars for which we have complete and reliable light curves and their location on the period-amplitude diagram suggest that CVn I is an Oosterhoff-intermediate type object. Thus CVn I seems to follow the trend of the other "classic" dSphs (Catelan 2004). This similarity is strengthened in that CVn I seems to contain a complex stellar population with components of different age in the range from 13 to 0.6 Gyr.

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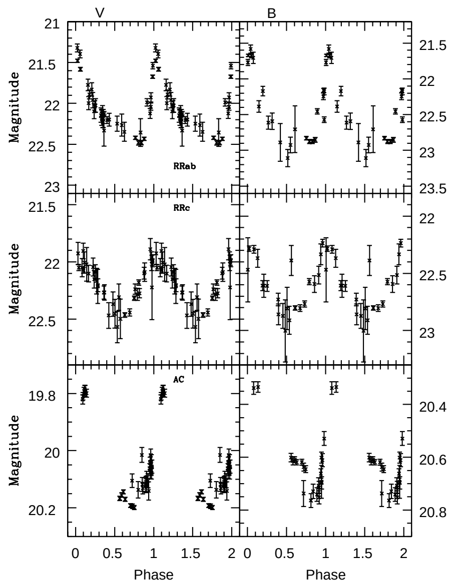

Fig. 1.— V and B light curves of variable stars in CVn I. *Top* : RRab star with P=0.63 days. *Middle* : RRc star with P=0.40 days. *Bottom* : candidate Anomalous Cepheid with a possible period of 1 day.

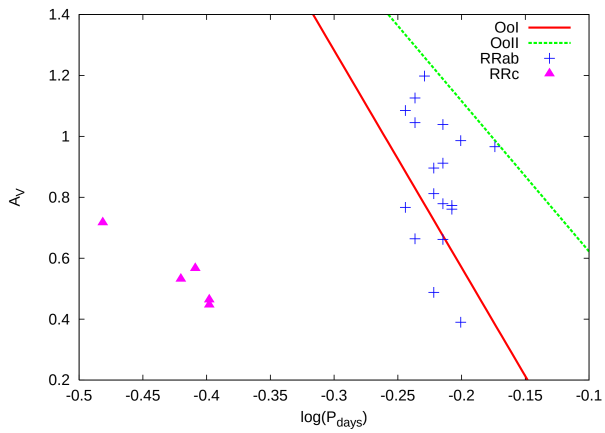

Fig. 2.— Period-amplitude diagram in the V band for the CVn I RR Lyrae stars. RRab stars are indicated by blue crosses and RRc stars are indicated by purple triangles. The solid and dashed lines are the positions of Oosterhoff type I (OoI) and Oosterhoff type II (OoII) Galactic globular clusters from Clement & Rowe (2000).

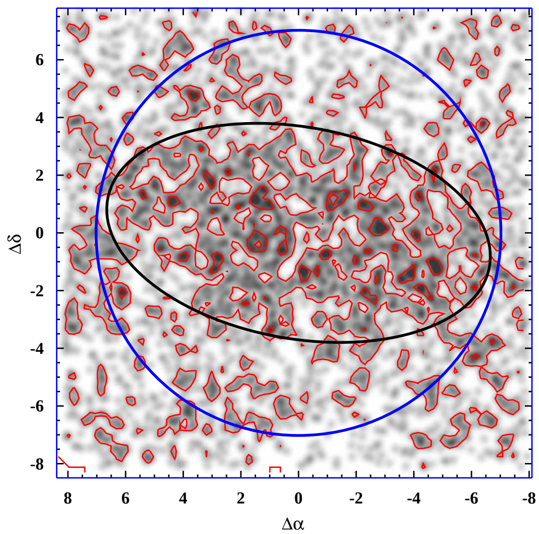

Fig. 3.— Smoothed map of the galaxy stars in the field of view of the WHT observations, in differential R.A. and declination from the CVn I dSph center. The bulk of the CVn I stars is within the black ellipse which has semi-major axis r= 6.7 arcmin and ellipticity e=0.55. The blue circle has a radius of r = 7 arcmin.

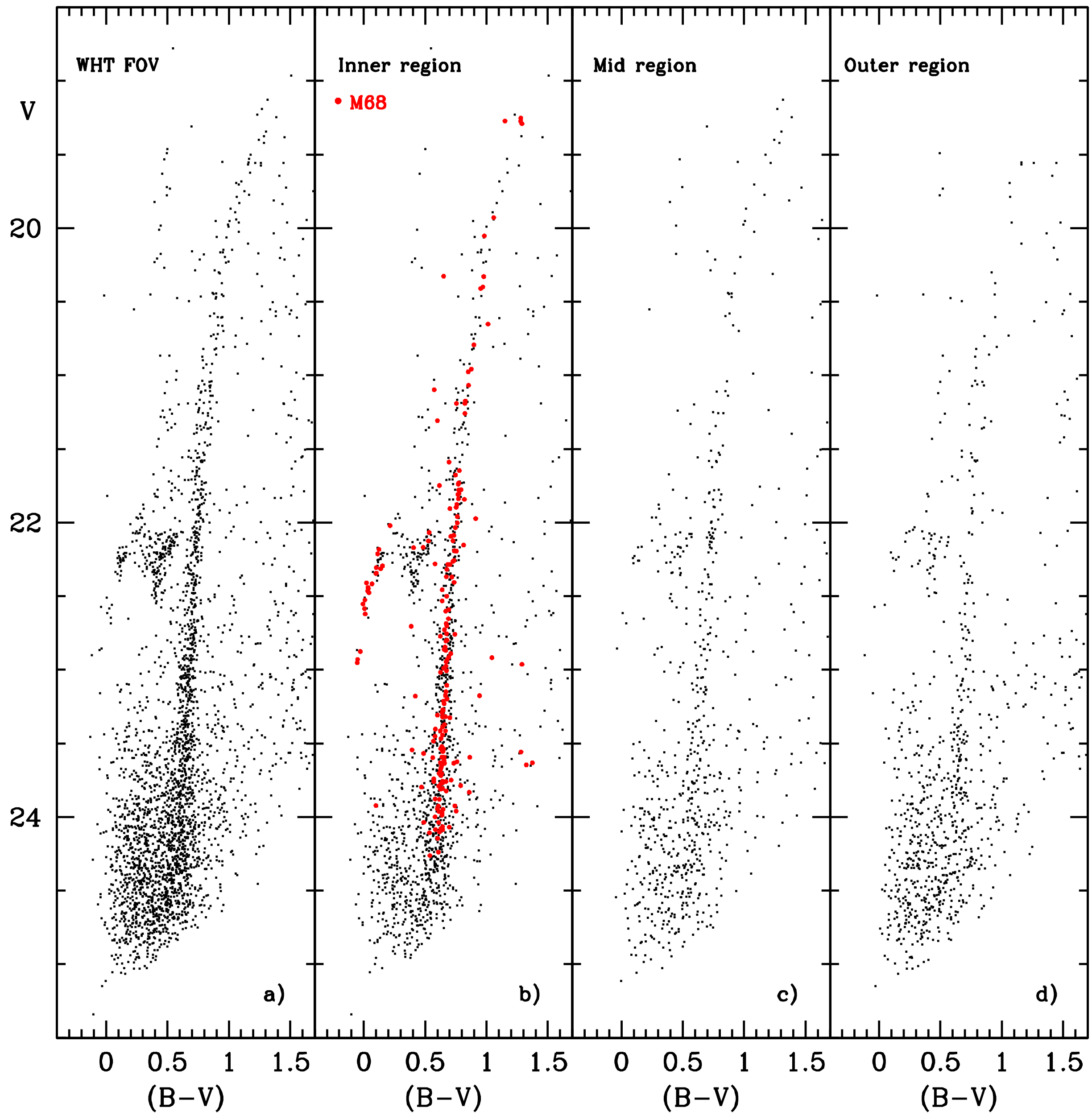

Fig. 4.— $V, B-V$ CMDs of the Canes Venatici I dwarf spheroidal galaxy obtained from stars in the whole 16.2×16.2 arcmin^2 field covered by the WHT observations (Fig. 4*a*); and in 3 separate regions corresponding to the black ellipse (Fig. 4*b*); the intermediate region between ellipse and blue circle (Fig. 4*c*); and the region outside the blue circle (Fig. 4*d*) of Figure 3 . Plotted in red are stars of the Galactic globular cluster M68, after Walker (1994).

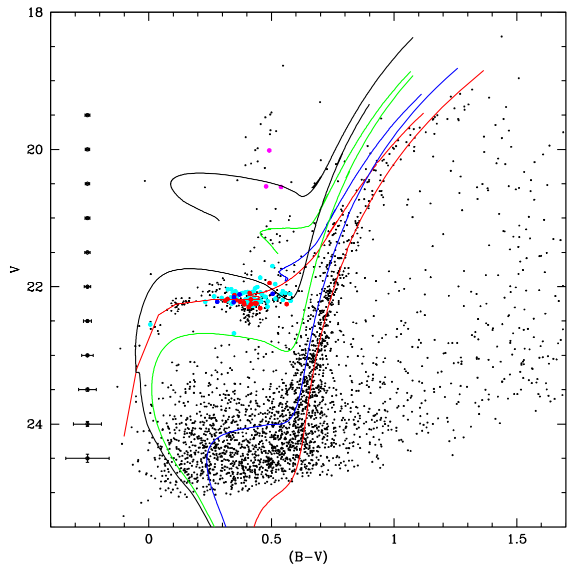

Fig. 5.— Best fit of the CVn I CMD in Fig. 4*a*, using isochrones from the Pisa dataset with Z=0.0002 ([Fe/H]=−2.0 dex), and 4 age components; 13 Gyr (*red line*), 5 Gyr (*blue line*), 1.5 Gyr (*green line*), and 0.6 Gyr (*black line*). The CVn I variable stars are plotted with different symbols: red, RRab stars; blue, RRc stars; cyan, candidate variables for which we were not able to derive reliable periods; purple, candidate ACs. Typical error bars of the photometry are provided on the left-hand side.